

Final Report on Proposal to  
AUGMENT 30CM FLYING INFRARED TELESCOPE PROGRAM  
National Aeronautics and Space Administration  
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F.J. Low  
University of Arizona

The 30cm infrared telescope developed by Low and co-workers was the first successful airborne infrared telescope to be flown in the open port mode which permits full wavelength coverage. This instrument was used extensively in a continuing program of far infrared astronomical observations. During the period of the subject grant, performance of the instrument was greatly augmented. Improvements were made in the inertial stabilization, which enabled much higher angular resolution and, in conjunction with improved detectors and filters, much higher sensitivity. The following list of publications resulted from this work:

- "Far Infrared Observations of the Galactic Center", Ap.J. Letters 159, L159-L164, 1970, F.J. Low and H.H. Aumann.
- "Closing Astronomy's Last Frontier--Far Infrared", Astro. & Aero. pp. 26-29, 1970, F.J. Low, H.H. Aumann and C.M. Gillespie, Jr.
- "Dark Nebulae, Globules & Protostars", University of Arizona Press, B.T. Lynds, Editor, 1971, F.J. Low.
- "Celestial Sources at 10 to 100 Microns", Classified Proceedings of the Eighth Midcourse Meeting, July, 1970, F.J. Low
- "Observations of Galactic and Extragalactic Sources Between 50 $\mu$  - 300 $\mu$ ", Ap.J. 162, L79-L85, 1970, F.J. Low and H.H. Aumann.
- "Infrared Observations of Comets 1969g and 1969i", Ap.J. 165, 855, 1971, F.J. Low, D. Kleinmann, T.A. Lee and C.R. O'Dell.
- "Far-Infrared Emission from HII Regions", Ap.J. 165, L9-L13, 1971, F.J. Low and D.A. Harper.

## CELESTIAL SOURCES AT 10 TO 100 MICRONS

Frank J. Low

Univ. of Arizona  
Tucson, ArizonaRice University  
Houston, Texas

Observations are carried out with three different systems:

(1) a multiband photometer which operates in all the atmospheric windows from 1 to 25 microns, (2) a 10 micron sky mapper using a 28-inch or a 21-inch telescope, (3) a 12-inch airborne telescope for wavelengths 50 to 300 microns. System (1) is used to make detailed studies of the spectral distribution, brightness, size and position of infrared sources. When used on the 61-inch telescope at the Catalina Observatory north of Tucson we can accurately measure 10 micron sources as faint as  $1 \times 10^{-18} \text{ w/cm}^2/\mu$  in 30 minutes. The angular diameter of the beam is 5 arcseconds and positional accuracy of  $\pm 1$  arcsecond is achieved by optical offsetting using an infrared beam splitter. System (2) has been in operation for a short period of time and a number of faint sources have been detected at levels above  $3 \times 10^{-16} \text{ w/cm}^2/\mu$ . One of these sources coincides with a source in Orion reported by Walker and Price found by a recent rocket survey. System (3) has been used to observe known infrared sources in the wavelength range not accessible from the ground. It has also been used to survey limited areas of the sky and a number of extremely bright,  $5 \times 10^{-13} \text{ w/cm}^2$ , sources have been found. Some of these sources have not yet been seen from the ground.

Based on our present knowledge we can draw the following

picture of the sky at 10 microns:

- (a) Solar System - Mercury, Venus, Mars, Jupiter, Saturn, the Galilean satellites, Titan and, when they are close to the Earth, several asteroids such as Ceres, and Vesta and most comets are brighter than  $1 \times 10^{16} \text{ w/cm}^2/\mu$ . Because of planetary motions and considerable temperature changes these sources are all variable.
- (b) Bright Stars: A  $10,000^\circ\text{K}$  star of zero visual magnitude produces a flux density at 10 microns of about  $1 \times 10^{-16} \text{ w/cm}^2/\mu$ ; Vega ( $\alpha$  Lyra) is such a star. Cooler stars become brighter in the infrared relative to their visual brightness. There are several stars which are about 100 times brighter than Vega at 10 microns. There must be several hundred stars which equal or exceed the brightness of Vega at 10 microns but the exact number is not yet known. Many of these stars are weakly variable at 10 microns.
- (c) "Infrared" Stars: The Northern sky has been surveyed at 2.2 microns by the Cal Tech group. Of the 5000 stars detected at 2.2 microns about 20 have been found to radiate large amounts of infrared compared to ordinary cool stars. Most of the  $\sim 80$  "infrared" stars which we have studied at 10 microns were found by observing members of certain special classes of stars which were suspected to have large infrared excesses. The infrared excess at 10 microns is produced by a cloud of dust surrounding the star which absorbs the hot radiation from the star and reradiates at a temperature between 50 to  $1400^\circ\text{K}$ . Many of these stars peak at 5 microns ( $T \approx 600^\circ\text{K}$ ). The cloud of dust is produced by mass ejection from the star.

Mass ejection is found in certain types of stars and can now be detected either by the resulting 10 micron excess radiation or by the presence of certain lines in their optical spectra. Using the optical spectra as a guide we have found many infrared stars. So called T tauri stars and many Fe emission stars are examples of this work. Recently we have found that Novae, which are stars which eject mass explosively rather than by continuous processes, become extremely bright infrared stars within a few days after outburst. There is evidence that infrared stars can be highly variable at 10 microns.

Indeed the number of such objects is constantly changing.

- (d) "Infrared Nebulae": A number of extended infrared sources have been found in our galaxy. These bodies are cooler than  $300^{\circ}\text{K}$  but extremely luminous,  $>10^6$  times the power output of the sun. At the center of the galaxy, in the constellation Sagittarius, there is a complex of extended sources which is most clearly seen at 50 to 100 microns. In most cases these sources are associated with so called H II regions, places where extremely hot stars ( $10^5$  to  $10^6^{\circ}\text{K}$ ) have completely ionized the hydrogen gas. Throughout the galaxy there are perhaps a few hundred such objects and most of them should be detectable at 10 microns at a flux level above  $1 \times 10^{-6} \text{ w/cm}^2/\mu$ . Examples are M17, M8, M42 and NGC7027. Almost all of these galactic sources, including the "infrared" stars are concentrated into a few thousand square degrees of the sky near the plane of the Milkyway, with the greatest concentration in the direction of the galactic center. Away from the plane of the galaxy these sources will be extremely rare.

- (e) "Infrared galaxies": Galaxies are randomly distributed on the celestial sphere and many galaxies are extraordinarily luminous in the infrared. Some galaxies are 100 to 1000 times more powerful in the infrared than at optical wavelengths. We have shown that the peak of the energy distribution is near 100 microns. 15 galaxies have been detected at 10 microns and two, M82 and NGC 1068, are as bright as  $1 \times 10^{-16} \text{ w/cm}^2/\mu$ . At lower flux levels the number of extra-galactic sources will become extremely high. At  $1 \times 10^{-19} \text{ w/cm}^2/\mu$  there should be about one source per sq. degree. M82 has been resolved at 10 microns into a source about  $15 \times 30$  arcseconds, however, most galaxies will appear as point sources and will vary with time scales as short as weeks.

## FAR-INFRARED EMISSION FROM H II REGIONS

D. A. HARPER

Rice University

AND

F. J. LOW

Rice University and University of Arizona

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## ABSTRACT

Large far-infrared (45–750  $\mu$ ) fluxes have been measured from eight sources associated with galactic H II regions. The far-infrared objects are coincident with the thermal radio sources DR 21, K3-50, M17, M42, NGC 2024, W49, and W51. An upper limit was also obtained for the planetary nebula NGC 7027. The far-infrared luminosities of the sources range from  $2 \times 10^4$  to  $2 \times 10^7 L_{\odot}$ . Measurements of M17, M42, NGC 2024, W49, and W51 indicate that the sources are extended, are optically thin, and have temperatures in the range 65°–120° K.

Low and Aumann (1970) observed large far-infrared fluxes from M17 and M42. In this Letter, we report the initial results of a more extensive study of far-infrared emission from galactic H II regions. Two of the objects which we observed were known to possess infrared continua which increase in intensity between 10 and 20  $\mu$  (Gillett, Low, and Stein 1967; Neugebauer and Garmire 1970). The remaining objects were chosen from Schraml and Mezger's (1969) list of 2-cm radio sources which, like M17 and M42, possess bright, compact ( $\sim 5'$  diameter), thermal components.

The 30-cm flying infrared telescope was described previously by Aumann and Low (1970) and Low, Aumann, and Gillespie (1970). A new two-axis gyrostabilization system has been added which provides tracking accuracies better than  $\pm 1'$ . Guiding errors caused by bore sighting of the optical guide telescope were  $\sim \pm 1'$ , while errors in off-setting from nearby field stars were, at times, several minutes of arc. Thus, our observations are generally subject to positional errors of a few minutes of arc and tend to give fluxes which are too low on weak signals. The angular separation of the two beams was  $14'$ .

The basic filter complement consists of 0.5 mm of sapphire and 0.5 mm of calcium fluoride in contact with a silicon field lens, all cooled to 1.8° K, and a 1-mm-thick, 32-mm-diameter disk of high-density polyethylene coated with 50 mg of 6- $\mu$  diamond particles which served as the Dewar window. In addition, there was a turret maintained in thermal contact with the helium reservoir which allowed interchange of auxiliary cooled filters and focal-plane diaphragms during the course of a flight. For this series of flights, the six turret positions were occupied by 5.2-, 3.2-, and 2.0-mm diaphragms, by 5.2- and 3.2-mm diaphragms combined with 0.5 mm of barium fluoride, and by an aluminum blank-off plate. The basic system has a low-pass cuton at 45  $\mu$  and less than 0.1 percent transmission throughout the stop band. Introduction of the barium fluoride into the beam moves the cuton to 60  $\mu$ . The low-frequency cutoff is determined by diffraction effects and occurs at 300  $\mu$  or more, depending on diaphragm size. The half-peak beam diameters corresponding to the 5.2-, 3.2-, and 2.0-mm diaphragm are, respectively,  $8.4 \pm 1'$ ,  $6.7 \pm 1'$ , and  $4.8 \pm 1'$ . The data reported here were obtained with the 5.2-mm diaphragm unless noted otherwise.

The absolute calibration is based on the assumption that Jupiter radiates as a 134° K

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blackbody (Aumann, Gillespie, and Low 1969). We estimate that the accuracy of the absolute calibration is approximately 25 percent. A standard reference source was not available on all flights. However, four sources (M17, M42, Saturn, and W51a) were observed on two or more separate flights with a maximum discrepancy of less than 15 percent in the recorded signal levels. Thus, we have set the smallest errors shown in Figure 1 at  $\pm 15$  percent.

The data are summarized in Table 1. Far-infrared fluxes given in column (4) refer to observations with the 45–750- $\mu$  passband and the 8'.4 beam. Color temperatures ( $T_c$ ) are based on the ratios of fluxes in the 45–750- $\mu$  and 60–750- $\mu$  passbands. Recently we have observed M42 with moderately narrow bandpass filters with equivalent wavelengths of 44.5 and 79  $\mu$ , and our preliminary analysis of these data indicates a color temperature of  $105^\circ(+12^\circ, -8^\circ)$  K. When the 2.0-mm diaphragm was substituted for the 5.2-mm diaphragm, the signals from M17, M42, and M51a decreased by 50, 30, and 30 percent, respectively. This implies that the diameters of these sources are a few minutes of arc, comparable to the radio diameters measured at 2 cm. Together with the calculated temperatures, this leads to the important conclusion that the sources are optically thin in the far-infrared.

Within the limits of our positions, all of the infrared sources coincide with bright thermal radio sources. The G numbers, references giving distances, and free-free flux densities of these sources are listed in Table 2. The infrared luminosities given in column (5) are based on the fluxes in Table 1 and the distances given for the radio sources. Note that these values do not include energy outside our bandwidth. The 2-cm flux densities of M17, M42, DR 21, NGC 2024, W49, W51a, and W51b refer to components which have been separated from a more extended background source. In no case, however, would the inclusion of the background result in a change in flux density of more than a factor of 2. The previously observed far-infrared sources Sgr IRA, IRB, and IRC (Low and Aumann 1970) have been included for comparison. The thermal radio sources which have been tentatively associated with Sgr IRA are near, but not coincident with, the nonthermal source Sgr A which is generally assumed to be located at the galactic center.

In Figure 1, we have plotted the observed infrared fluxes against the free-free flux densities in an effort to examine the relationship between the infrared luminosities of the H II regions and the intrinsic luminosities of the exciting stars. The two points given for the double source M17 correspond to the alternative assumptions that both radio sources were included in our beam and that just the brighter one was included. The two points for Sgr IRA refer to the two thermal radio sources separately. Rubin (1968)

TABLE 1  
SUMMARY OF DATA

Source (1)	$\alpha(1950.0)$ (2)	$\delta(1950.0)$ (3)	$F_{\text{IR}}$ ( $10^{-14}$ W cm $^{-2}$ ) (4)	$T_c$ ( $^\circ$ K) (5)
DR 21.....	20 <sup>h</sup> 37 <sup>m</sup> 13 <sup>s</sup> $\pm$ 32 <sup>s</sup>	42 <sup>o</sup> 09' $\pm$ 6'	8.8	...
K3-50.....	20 <sup>h</sup> 00 <sup>m</sup> $\pm$ 1 <sup>m</sup>	33 <sup>o</sup> 24' $\pm$ 12'	5.0	...
NGC 7027.....	21 <sup>h</sup> 05 <sup>m</sup> 09 <sup>s</sup>	42 <sup>o</sup> 02'03"	< 1.2	...
NGC 2024.....	05 <sup>h</sup> 39 <sup>m</sup> 08 <sup>s</sup> $\pm$ 24 <sup>s</sup>	— 1 <sup>o</sup> 55' $\pm$ 6'	42	70(+20, -15)
M17.....	18 <sup>h</sup> 17 <sup>m</sup> 35 <sup>s</sup> $\pm$ 15 <sup>s</sup>	— 16 <sup>o</sup> 11' $\pm$ 3'	73	85(+25, -15)
M42.....	05 <sup>h</sup> 32 <sup>m</sup> 50 <sup>s</sup> $\pm$ 4 <sup>s</sup>	— 5 <sup>o</sup> 25' $\pm$ 1'	186	100(+20, -12)
W49.....	19 <sup>h</sup> 07 <sup>m</sup> 56 <sup>s</sup> $\pm$ 16 <sup>s</sup>	9 <sup>o</sup> 03' $\pm$ 4'	31	70(+20, -15)
W51a.....	19 <sup>h</sup> 21 <sup>m</sup> 23 <sup>s</sup> $\pm$ 12 <sup>s</sup>	14 <sup>o</sup> 26' $\pm$ 3'	64	70(+20, -15)
W51b.....	19 <sup>h</sup> 20 <sup>m</sup> 50 <sup>s</sup> $\pm$ 20 <sup>s</sup>	14 <sup>o</sup> 20' $\pm$ 5'	12	...

TABLE 2  
SUMMARY OF DATA

Source (1)	G (2)	Reference (3)	2-cm Flux Density ( $10^{-26}$ W m $^{-2}$ Hz $^{-1}$ ) (4)	L <sub>IR</sub> ( $L_{\odot} \times 10^4$ ) (5)
DR 21.....	81.7 $\pm$ 0.5	1	19.0	0.62
K3-50.....	...	2	10	11
NGC 7027.....	...	2	7	< 0.12
NGC 2024.....	206.6-16.4	1	42.4	0.21
M17.....	15.0- 0.7	1	160.5	11
	15.1- 0.7		166.6	
M42.....	209.0-19.4	1	238	1.6
W49.....	43.2+ 0.0	1	38.5	190
W51a.....	49.5- 0.4	1	72.1	84
W51b.....	49.4- 0.3	1	15.9	15
Sgr IRA.....	0.1+ 0.0	3	60	170
	0.2+ 0.0		130	
Sgr IRB.....	0.7+ 0.0	3	45	150
Sgr IRC.....	- 0.6- 0.1	3	12	56

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1. Schraml and Mezger (1969).
2. Rubin and Turner (1969).
3. Downes and Maxwell (1966).

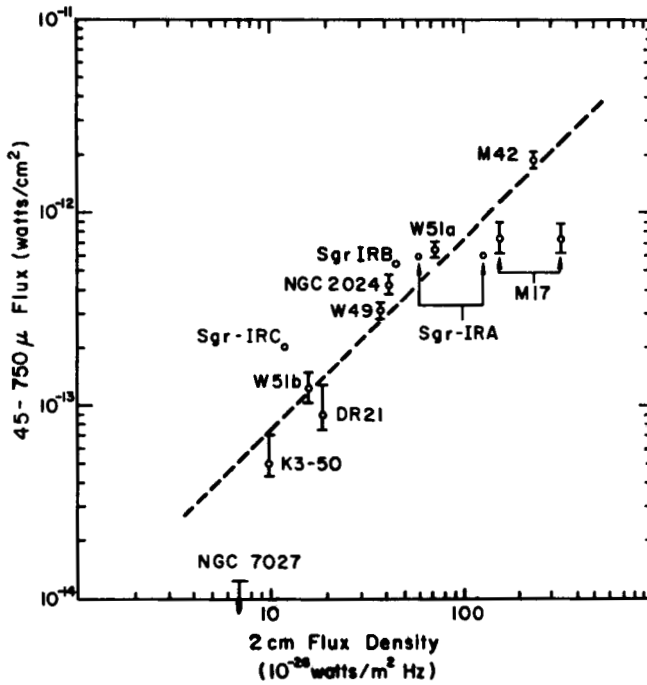


FIG. 1.—Observed far-infrared flux as a function of 2-cm flux density. Points without error bars from Low and Aumann (1970). Dashed line has unity slope.

has shown that if the electron temperature does not vary drastically within an H II region, the free-free flux density at a frequency for which the nebula is optically thin can be related, through the equation of global ionization equilibrium, to the primary flux of Lyman-continuum photons exciting the region. Krishna Swamy and O'Dell (1968) have suggested that  $L\alpha$  photons may be efficiently converted into infrared radiation through heating of nebular dust grains. This would result in a linear relation between infrared flux and free-free flux density, just as the data of Figure 1 suggest. However, if we assume that each Lyman-continuum photon is eventually degraded into a  $L\alpha$  photon and use Rubin's expression to calculate the total power  $P\alpha$  available in that form, we find that  $L_{\text{IR}}$  exceeds  $P\alpha$  by an average factor of 5.5. Thus, one of the following conditions must hold: (1) the dust is competing effectively with the gas for primary Lyman-continuum photons and the nebulae are essentially "dust bounded," (2) the dust is heated by strong local sources which radiate primarily at wavelengths longer than the Lyman limit, or (3) the infrared is emitted by the gas in the form of line radiation. Although our observations are not conclusive, they strongly favor the first alternative and are consistent with continuum radiation from relatively small source regions of approximately the same dimensions as the radio sources.

Our 45-750- $\mu$  system measures a major fraction of the total infrared emission; for the hottest object measured, M42, this fraction is about 50 percent. A narrow bandwidth would clearly degrade the linear relation of Figure 1.

Suppose that thermal reradiation from dust mixed with the ionized gas is the correct radiative mechanism. We can estimate the total mass in the form of grains required to produce a given infrared-source luminosity by means of the relation

$$m_d = \frac{L\rho a}{3\epsilon\sigma T^4}, \quad (1)$$

where  $\rho$ ,  $a$ ,  $T$ , and  $\epsilon$  are, respectively, the density, radius, temperature, and far-infrared emissivity of the particles. From abundance arguments, a plausible model should satisfy the requirement that

$$m_d < 0.01 m_{\text{H}}. \quad (2)$$

where  $m_{\text{H}}$  is the total mass of hydrogen occupying the same volume as the radiating dust. From the radiofrequency continuum Schraml and Mezger (1969) have calculated the mass of ionized hydrogen in seven of the observed H II regions. In Table 3 we have listed values for  $m_d$  and  $m_d/m_{\text{H II}}$  calculated for the source under the assumptions that  $a = 0.02 \mu$ ,  $\rho = 1 \text{ g cm}^{-3}$ , and  $\epsilon_{\text{IR}} = 0.005$ , and for  $L_{\text{IR}}$  and  $T$  equal to the values given in Tables 1 and 2. We have arbitrarily assigned a value of 70° K to DR 21 and W51b. It is probably significant that equation (2) can be approximately satisfied for most of

TABLE 3  
MASS FRACTIONS OF DUST GRAINS

Source	$m_d/m_{\odot}$	$m_d/m_{\text{H II}}$
DR 21.....	0.12	> 0.1
NGC 2024.....	0.040	0.0026
M17.....	1.4	0.0064
		0.0042
M42.....	0.074	0.011
W49.....	36	0.0096
W51a.....	16	0.018
W51b.....	2.9	0.0056

the sources by a single value of the product  $\rho a/\epsilon$ . The values for  $\rho$  and  $a$  are typical for interstellar dust.

Thus, our observations appear to be consistent with a model in which dust grains, present in the original cloud of gas from which the nebula was formed, are heated to temperatures of the order of 55°–120° K by the ultraviolet radiation from luminous stars within the nebula. The fact that the sources are optically thin and extremely bright means that the radiative properties of the dust can be determined over a wide spectral range, and hopefully this will lead to a better understanding of the composition of such material. The fact that the infrared luminosities exceed, by about 5 times, the  $L\alpha$  luminosities calculated from the free-free flux densities suggests that the dust may exert a significant influence on the structure and extent of the ionized regions. Infrared measurements of higher spectral and spatial resolution and covering a wider class of H II regions should further clarify the significance of the linear relation suggested by Figure 1.

The galactic-center region is of special interest, since it contains many discrete H II regions plus a general background of thermal radio emission. It now appears that the three discrete sources Sgr IRA, IRB, and IRC (Low and Aumann 1970) can be accounted for by the general mechanism acting in H II regions and that the more diffuse far-infrared emission reported by Hoffmann and Frederick (1969) is of similar origin. Thus, only the small cluster of sources observed between 5 and 25  $\mu$  at the center of Sgr A remains unexplained.

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OBSERVATIONS OF GALACTIC AND EXTRAGALACTIC  
SOURCES BETWEEN 50 AND 300 MICRONS

F. J. Low

University of Arizona, Tucson, Arizona, and Rice University, Houston, Texas

AND

H. H. AUMANN

Rice University, Houston, Texas

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## ABSTRACT

We report far-infrared observations of the galactic nucleus, of two discrete sources near the galactic nucleus, of two sources associated with H II regions, and of two extragalactic sources. All these objects have spectral distributions peaking between 50 and 300  $\mu$ , and their luminosities range from  $1.6 \times 10^8$  to  $2 \times 10^{12} L_{\odot}$ .

## I. INTRODUCTION

Ground-based observations out to 25  $\mu$  revealed that a number of galactic and extragalactic infrared sources radiate much of their energy beyond 25  $\mu$ , wavelengths which do not penetrate the water vapor in the lower atmosphere. An infrared telescope operated at aircraft altitudes now permits routine observations in the spectral band 50–300  $\mu$ . This system was described by Low, Aumann, and Gillespie (1970), and a number of results have been reported (Aumann, Gillespie, and Low 1969; Aumann and Low 1970; Low 1970). Observations of the planets are continuing and will be described later; here we report results concerning both galactic and extragalactic sources. Two of these sources are extremely bright in the 50–300- $\mu$  band but are so cold that they have not been detected from the ground; they appear to be members of a new class of galactic objects having luminosities greater than  $10^7 L_{\odot}$ . It is possible that thermal reradiation from dust heated by thermonuclear energy can account for all the galactic sources. New results favoring this type of model for the galactic nucleus are presented. The spectral distributions of the galactic and extragalactic sources are roughly similar, suggesting the possibility of a common physical process. Decisive observations have not yet been made; but as data are accumulated, it appears that both thermal and nonthermal infrared radiation is emitted by galaxies and that thermonuclear energy sources alone are inadequate.

## II. INSTRUMENTATION AND CALIBRATION

Observational techniques have already been described (Aumann and Low 1970). Here it is important to note the following points. The angular separation of the two beams was always equal to or greater than the beam diameter, which was varied from 3'5 to 14'. The output signal is proportional to the difference between the power radiated into each of the beams. The telescope is thus sensitive to point sources and gradients of extended sources, but not to a uniform background. The transmission cut-on of the system at 50  $\mu$  was defined by a Teflon filter 1.6 mm thick and a black polyethylene filter 0.3 mm thick, both cooled to 2° K. The rejection short of 50  $\mu$  was better than  $10^3$ . Diffraction limited the response of the system beyond 300  $\mu$ .

Our observations yield broad-band 50–300- $\mu$  integrated flux measurements and are calibrated relative to Mars, Jupiter, and Saturn. We have measured the effective temperatures of these planets to be  $(234 \pm 6)^{\circ}$ ,  $(134 \pm 5)^{\circ}$ , and  $(97 \pm 3)^{\circ}$  K, respectively (Aumann *et al.* 1969). It is assumed that over the 50–300- $\mu$  band the spectral distribu-

tions and brightnesses of the planets can be approximated by blackbodies at these temperatures. The validity of this assumption was tested by intercomparing these three planets on several flights, and we found that relative deflections were predictable to within 10 percent; however, the 50–300- $\mu$  brightness temperature of Venus as determined relative to Jupiter was  $(276 \pm 25)^\circ\text{K}$ , above the values  $(221 \pm 10)^\circ$  and  $(248 \pm 10)^\circ\text{K}$  obtained at 10 and 22  $\mu$  by Low (1966). The errors in the fluxes reported here reflect only statistical errors deduced from the observations and do not include the error in the absolute calibration, which is thought to be approximately  $\pm 10$  percent.

Pointing is accomplished by means of an optical telescope bore-sighted to the infrared telescope. Positional accuracies of  $\pm 2'$  have been achieved. Scan rates are not uniform and are affected by aircraft motions; however, long integrations are possible under favorable conditions.

### III. OBSERVATIONAL RESULTS

#### a) *Region of the Galactic Center*

With a beam diameter of  $7'$  we can distinguish three discrete sources in an area extending  $\pm 1.5^\circ$  along and  $\pm 1^\circ$  to the north and south of the galactic plane, centered on Sgr A.

Table 1 lists the positions of these sources, referred to as Sgr IRA, Sgr IRB, and Sgr IRC. Observations with beam sizes ranging from  $3.5'$  to  $14'$  (full width at half-peak) are listed in Table 2 in terms of the total flux directly observable between 50 and 300  $\mu$ ,  $F_{50-300}(\text{W cm}^{-2})$ . The observed deflections relative to Jupiter increase with increasing beam diameters. We interpret these beam-size effects as due to the extended nature of the sources. Figure 1 shows that the flux  $F_{50-300}$  increases for Sgr IRA as (beam diameter) $^{0.9 \pm 0.2}$ . The fluxes from Sgr IRB and Sgr IRC increase at slower rates, approximately as (beam diameter) $^{0.6 \pm 0.2}$ .

Typical scans parallel to the chopping direction through Sgr IRA, Sgr IRB, and Jupiter are shown in Figure 2. The scan through Sgr IRA was made at an angle of approximately  $60^\circ$  to the galactic equator and extends from near  $1^\circ$  to the east to  $1^\circ$  to the west of the galactic center. The extended nature of the source, deduced from observations of beam-size effects, is not immediately apparent from scans; nor is there evidence of the large  $2^\circ \times 6^\circ$  source reported by Hoffmann and Frederick (1969). However, the gradient of the radiation from such a source may be sufficiently low that the signal produced by our differential chopping technique is lost in the noise level. The scan shown in Figure 2a could thus be compatible with a source  $10'-15'$  in diameter superimposed on a much more extended source with a flux gradient of the order of  $4 \times 10^{-13} \text{ W cm}^{-2} \text{ degree}^{-1}$ . If a width of  $2^\circ$  is assumed, the luminosity of the extended source could be near  $4 \times 10^8 L_\odot$ , comparable to Hoffmann and Frederick's (1969) result.

Observations of Sgr IRA and Sgr IRB with 20 percent spectral resolution at 65 and 105  $\mu$  are still in preliminary analysis but suggest continuum radiation rather than one or a small number of emission lines. For frequencies between  $6 \times 10^{12}$  and  $10^{12} \text{ Hz}$  a continuum distribution given by

$$\begin{aligned} F &= (F_\nu)_{\text{max}} (\nu/\nu_{\text{max}})^{-3.5 \pm 0.5} & (\nu \geq \nu_{\text{max}}), \\ F &= (F_\nu)_{\text{max}} (\nu/\nu_{\text{max}})^{3.5 \pm 0.5} & (\nu < \nu_{\text{max}}), \end{aligned} \quad (1)$$

can be fitted to the observations.  $(F_\nu)_{\text{max}}$ ;  $\nu_{\text{max}}$ ; the extrapolated integrated flux between 10 and 300  $\mu$ ,  $F_{10-300}$ ; and the total infrared luminosity,  $L_{10-300}$ , for observations with a  $3.5'$  beam are listed in Table 2. We have assumed that all three sources are at a distance of 10 kpc.

Figure 3 shows the spectral power distribution for Sgr IRA with the  $3.5'$  beam. Observations at 5, 10, and 22  $\mu$  reveal the existence of a source  $\sim 15''$  in diameter. Recent

TABLE 1  
OBSERVED AND CALCULATED PARAMETERS

PARAMETER	Sgr IRA	Sgr IRB	Sgr IRC	M17	Ori IRA+IRB	NGC 1068	M82
Coordinates (1950):							
$\alpha$ . . . . .	17 <sup>h</sup> 42 <sup>m</sup> 5	17 <sup>h</sup> 44 <sup>m</sup> 4	17 <sup>h</sup> 41 <sup>m</sup> 4	18 <sup>h</sup> 18 <sup>m</sup>	5 <sup>h</sup> 32 <sup>m</sup> 8	2 <sup>h</sup> 40 <sup>m</sup> 1	9 <sup>h</sup> 51 <sup>m</sup> 7
Distance (pc) . . . . .	-28°59'	-28°22'	-29°26'	-16°18'	-5°24'	-00°17'	69°55'1
Beam diameter (min of arc) . . . . .	10"	10"	10"	1800	500	1.3×10 <sup>7</sup>	3.2×10 <sup>8</sup>
$F_{50-300}$ (10 <sup>-14</sup> W cm <sup>-2</sup> ) . . . . .	7±1	7±1	7±1	7±1	90±1	7±1	8±1
$F_{max}$ (10 <sup>12</sup> Hz) . . . . .	54±3	49±6	18±4	70±10	80±10	2.5±0.7	< 6
$(F_{\nu})_{max}$ (10 <sup>-22</sup> W m <sup>-2</sup> Hz <sup>-1</sup> ) . . . . .	4.5±0.3	3.8±0.3	4.5*	4.5*	4.5*	4.5*	< 4.5*
$(F_{\nu})_{max}$ (10 <sup>-22</sup> W m <sup>-2</sup> Hz <sup>-1</sup> ) . . . . .	43±4	32±3	14	56	7	1.5±0.5	< 4
$F_{10-300}$ (W cm <sup>-2</sup> ) . . . . .	1.3×10 <sup>-12</sup>	6.4×10 <sup>-13</sup>	4.3×10 <sup>-13</sup>	1.7×10 <sup>-12</sup>	2.2×10 <sup>-12</sup>	4.2×10 <sup>-14</sup>	<10 <sup>-13</sup>
$L_{10-300}$ ( $L_{\odot}$ ) . . . . .	3.5×10 <sup>7</sup>	1.7×10 <sup>7</sup>	1.2×10 <sup>7</sup>	1.3×10 <sup>8</sup>	1.6×10 <sup>8</sup>	2×10 <sup>12</sup>	< 6×10 <sup>11</sup>

**\* Assumed.**

observations at  $10\ \mu$  show structure smaller than  $15''$  but less than 20 percent increase in flux with beam diameter from  $25''$  to  $120''$ . Therefore, the published  $5\text{--}24.5\text{-}\mu$  flux densities (Low *et al.* 1969) are plotted. The spectral power distribution of Sgr A at centimeter wavelengths is taken from the literature and is based on beam diameters  $\sim 3'$ . The upper limit at  $1\text{ mm}$  was obtained with a  $1'$  beam.

The fact that we have failed to detect Sgr IRB at  $10\ \mu$  with a  $2'$  beam indicates an upper limit well below the flux density of Sgr IRA. This is consistent with the results based on narrow-band observations which show that the peak flux density of Sgr IRB occurs at a significantly lower frequency than for Sgr IRA.

Scans were made with the  $3.5'$  beam between Sgr IRA and Sgr IRB, and no detectable flux was observed.

TABLE 2

## BEAM-SIZE EFFECT

Beam diameter (min of arc)	$3.5 \pm 0.5$	$7 \pm 1$	$8 \pm 1$	$14 \pm 2$
Chopper throw (min of arc)	9	9	9	14
$F_{10-300}(10^{-3}\text{ W cm}^{-2})$ :				
Sgr IRA.....	$2.9 \pm 0.3$	$5.4 \pm 0.2$	$6.0 \pm 1.2$	$11 \pm 2$
Sgr IRB.....	$3.4 \pm 0.2$	$4.8 \pm 0.5$	$6.4 \pm 1.2$	...
Sgr IRC.....	...	$2.5 \pm 0.9$	...	$3.4 \pm 0.5$

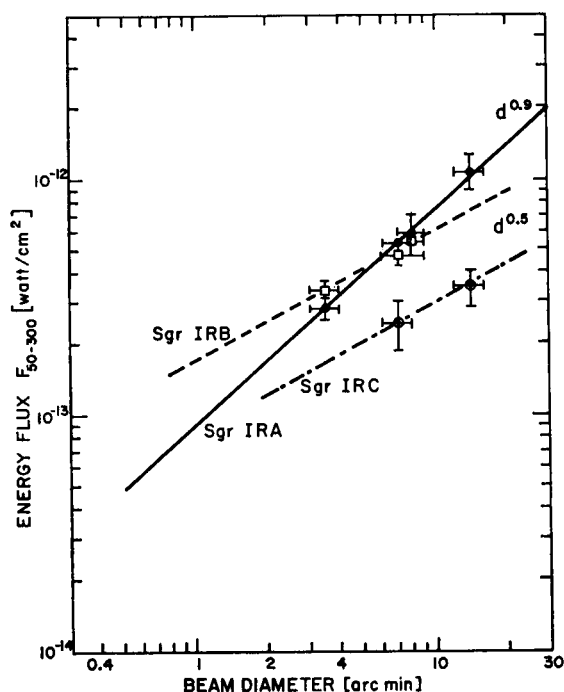


FIG. 1

FIG. 1.—The  $50\text{--}300\text{-}\mu$  energy fluxes of Sgr IRA, Sgr IRB, and Sgr IRC increase with increasing beam sizes.

FIG. 2.—Scans through Sgr IRA, Sgr IRB, and Jupiter with a  $7'$  beam and  $9'$  chopper throw. Scan through Sgr IRA extends from  $\sim 1^\circ$  east to  $1^\circ$  west of the galactic plane (markers relative to  $\chi$  Sgr). The manually controlled scan rates differ on the three scans.

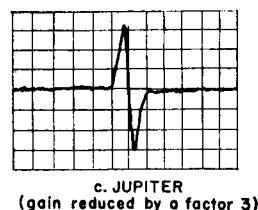
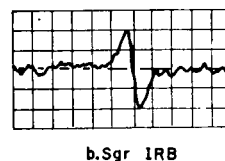
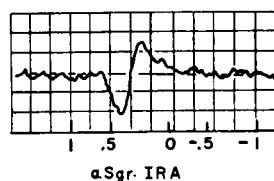


FIG. 2

b) *The Trapezium Region in Orion*

Observations of the Trapezium region in Orion with an 8' beam and 9' chopper throw have resulted in  $F_{50-300} = (1.5 \pm 0.2) \times 10^{-12} \text{ W cm}^{-2}$  (Table 2). Although our beam contains at least three infrared objects—the Becklin-Neugebauer (1967) point source at  $2.2 \mu$ , the Ney-Allen (1969) source (Ori IRA), and the Kleinmann-Low (1967) source (Ori IRB)—and the radio source Orion A, we believe that the cool wings of Ori IRB dominate the far-infrared emission. Observations at  $60 \mu$  with 20 percent spectral resolution indicate that the peak of the spectral power distribution falls near  $4.5 \times 10^{12} \text{ Hz}$ . Assuming the spectral power distribution given in equation (1), we calculate  $L_{10-300} = 1.6 \times 10^5 L_{\odot}$  at a distance of 500 pc. Observations with a 3' beam and passband from 1.5 to  $300 \mu$  (Aumann, Kleinmann, and Low 1971) result in a total infrared luminosity for Ori IRA plus Ori IRB of  $1.5 \times 10^5 L_{\odot}$ . Figure 3 shows the far-infrared spectrum and

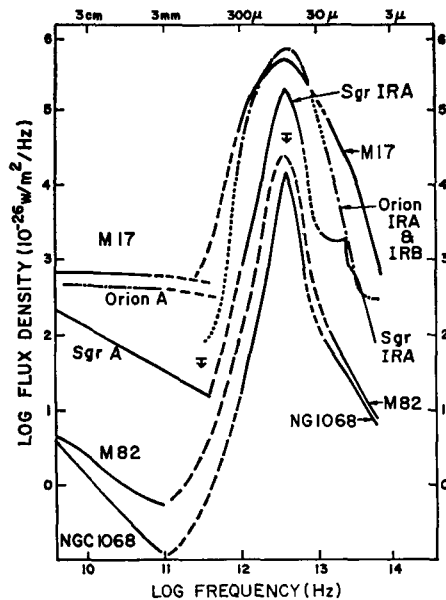


FIG. 3.—Spectral power distributions of the galactic and extragalactic sources. Data are lacking for wavelength intervals where dashed lines are shown. Upper limits applied to M82 at  $70 \mu$  and to Sgr A at  $1000 \mu$ .

the 10- and  $20\text{-}\mu$  flux densities for a 2' beam (Aumann *et al.* 1971). From 10 to  $100 \mu$ , the spectral distribution can be approximated by a  $75^\circ \text{K}$  blackbody. Beyond  $100 \mu$  the deduced spectrum falls off much more steeply than a blackbody, in agreement with the 100 f.u. which were observed at 1 mm with a 1' beam centered on Ori IRB.

c) *M17*

M17 is a galactic H II region which has been resolved at centimeter wavelengths into a double source about 5' by 12' (Schraml and Mezger 1969). Observations with a 7' beam and a 9' chopper throw result in a  $50\text{--}300\text{-}\mu$  flux of  $(7 \pm 2) \times 10^{-13} \text{ W cm}^{-2}$ . In order to calculate the flux density and total luminosity given in Table 2, we have assumed the continuum spectrum defined by equation (1) with  $\nu_{\text{max}} = 4.5 \times 10^{12} \text{ Hz}$  and a distance of 1.8 kpc (Allen 1962). The spectral power distribution is plotted in Figure 3, including the 5-, 10-, and  $22\text{-}\mu$  flux densities for the double source given by Kleinmann (1970).

## d) NGC 1068

Observations of the Seyfert galaxy NGC 1068 with a 7' beam and a 9' chopper throw produced an integrated 50–300- $\mu$  flux  $F_{50-300} = (2.5 \pm 0.7) \times 10^{-14} \text{ W cm}^{-2}$ . The 7' beam contains essentially the whole galaxy. Assuming that the spectral power distribution can be approximated by equation (1), and  $\nu_{\text{max}} = 4.5 \times 10^{12} \text{ Hz}$ , we obtain a luminosity  $L_{10-300} = 2 \times 10^{12} L_{\odot}$ , of which  $1.2 \times 10^{12} L_{\odot}$  is radiated between 60 and 300  $\mu$ . This is based on a distance of 13 Mpc, assuming a Hubble constant  $H_0 = 75 \text{ km sec}^{-1} \text{ Mpc}^{-1}$  (Sandage 1968). The measured total infrared luminosity of NGC 1068 is a factor of 3 below the luminosity deduced by Kleinmann and Low (1970a) under the assumption that the ratio of the 10- $\mu$  flux density to the total infrared flux is the same for all galaxies including the galactic nucleus. This is clearly not the case when there are large beam-size effects. At 5, 10, and 22  $\mu$  Kleinmann and Low (1970a) found no beam-size effects down to 5'' and  $L_{5-25} = 2 \times 10^{11} L_{\odot}$ . The spectral power distribution of NGC 1068 is plotted in Figure 3.

## e) M82

Observations of M82 established only an upper limit of  $F_{50-300} = 6 \times 10^{-14} \text{ W cm}^{-2}$ , when a 7' beam was used. This upper limit is a factor of 3 above the flux observed for NGC 1068. Again assuming the validity of equation (1) with  $\nu_{\text{max}} = 4.5 \times 10^{12} \text{ Hz}$  and a distance of 4.3 Mpc, we calculate  $L_{10-300} < 6 \times 10^{11} L_{\odot}$ . It is interesting to note that the fluxes measured at 5, 10, and 22  $\mu$  for M82 and NGC 1068 are quite similar (Kleinmann and Low 1970a). At 10  $\mu$ , M82 extends  $15'' \times 30''$  along its galactic plane (Kleinmann and Low 1970b).

## IV. SUMMARY

There are far-infrared sources in H II regions which emit a large fraction of the total luminosity of the system. Orion IRA and Ori IRB are so close together that the far-infrared observations cannot be interpreted unambiguously, but it appears that Ori IRB, which is not an H II region, may account for most of the flux. Sagittarius IRB is near but not coincident with the H II region Sgr B2. All five of the galactic sources reported here are associated with sources of molecular line emission in the microwave and millimeter-wave spectrum. This implies a direct physical relation between the two classes of phenomena and suggests the existence of many additional far-infrared sources.

The luminosity of Sgr IRB appears to be greater than  $10^7 L_{\odot}$ . Comparable power may be emitted by  $\eta$  Car, a much hotter infrared source observed by Westphal and Neugebauer (1969). It is possible that thermonuclear energy released by one or more massive stars is reradiated by dust as in the sources embedded in H II regions. For a temperature of 75° K, the far-infrared emissivity is only about 1 percent or less for all the galactic sources, indicating that they are optically thin.

In addition to the radio source Sgr A and the ensemble of stars observed by Becklin and Neugebauer (1968), the galactic nucleus contains at least two infrared components, (a) the small-diameter complex at an apparent temperature of 230° K embedded in (b) an extended halo at an apparent temperature of 75° K. Outside the immediate region of the nucleus there are the two luminous infrared sources colder than 70° K and a diffuse background extending along the galactic equator observed by Hoffmann and Fredrick (1969). The infrared luminosity of the nucleus increases almost linearly with diameter over the range 10–40 pc. Becklin and Neugebauer (1968) independently arrived at the same result for the luminosity of ordinary stars; furthermore, the total infrared luminosity within a given volume is almost equal to the stellar luminosity. A thermal-reradiation model utilizing the thermonuclear energy of the stars is suggested for the extended component. The highly structured small component may be nonthermal.

Before the beam-size effects at 70  $\mu$  were found, it was assumed (Low 1970) that a

common physical mechanism was at work in the nuclei of all galaxies. Note that if the region of the galactic center were observed from a great distance, the spectrum would be much steeper than the spectrum of NGC 1068, thus greatly weakening the assumption of commonality.

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FAR-INFRARED OBSERVATIONS OF THE  
GALACTIC CENTER

H. H. AUMANN AND F. J. LOW

## FAR-INFRARED OBSERVATIONS OF THE GALACTIC CENTER

H. H. AUMANN

Space Science Department, Rice University

AND

F. J. LOW

Space Science Department, Rice University, and Lunar and Planetary Laboratory,  
University of Arizona

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### ABSTRACT

The center of our Galaxy has been observed between 40 and 350  $\mu$ . The measured peak flux of  $(8 \pm 3) \times 10^{-21} \text{ W m}^{-2} \text{ Hz}^{-1}$  at  $(4.2 \pm .2) \times 10^{12} \text{ Hz}$  corresponds to a total integrated infrared flux at the Earth of  $(2.8 \pm 1.0) \times 10^{-5} \text{ erg sec}^{-1} \text{ cm}^{-2}$ . If a distance of  $10^4 \text{ pc}$  is assumed, the total infrared luminosity of the galactic nucleus is  $(8 \pm 3) \times 10^7 L_{\odot}$ . The far-infrared diameter of the nucleus is less than  $3'$  (10 pc), and its position agrees to within  $6'$  with the position of Sag A. Size and luminosity considerations strongly favor a nonthermal model of the galactic nucleus which consists of multiple sources. A number of discrete sources with flux levels of about  $1.5 \times 10^{-21} \text{ W m}^{-2} \text{ Hz}^{-1}$  were found near the galactic nucleus.

### I. INTRODUCTION

In a recent paper on the infrared spectrum, diameter, and polarization of the galactic nucleus (Low *et al.* 1969), we included a preliminary measurement of the galactic nucleus at 100  $\mu$ . This result led to the important conclusion that the nucleus of our Galaxy shares with infrared galaxies and QSOs a mechanism which produces an enormous amount of far-infrared radiation. In 1969 August we again observed the galactic center with a signal-to-noise ratio that was 10 times better and with significantly improved offset-guiding capability. Two different filter systems provided increased spectral resolution between 40 and 350  $\mu$ .

Our new measurements indicate that the far-infrared diameter of the galactic nucleus is less than  $3'$  ( $\approx 10 \text{ pc}$ ). The peak flux of  $(8 \pm 3) \times 10^{-21} \text{ W m}^{-2} \text{ Hz}^{-1}$  occurs at  $(4.2 \pm 0.2) \times 10^{12} \text{ Hz}$  and corresponds to a total integrated infrared flux at the Earth of  $(2.8 \pm 1.0) \times 10^{-5} \text{ erg sec}^{-1} \text{ cm}^{-2}$ . If a distance of  $10^4 \text{ pc}$  is assumed, the total infrared luminosity of the galactic nucleus is  $(8 \pm 3) \times 10^7 L_{\odot}$ . This is 5 times more than the power radiated by stars in a 10-pc volume and about 0.01 of the total power output of the Galaxy.

The upper limit on the diameter and the measured total power output strongly favor a nonthermal model of the galactic nucleus.

The extended source reported by Hoffmann and Fredrick (1969) was not detected, but several weak discrete sources were found. The apparent increase in flux over our preliminary result (Low *et al.* 1969) is not believed to be real; the difference has been traced to an overestimation of the effective system bandwidth and to a substantial error in offset guiding.

### II. INSTRUMENTATION

The observations were made with a 12" Cassegrain telescope mounted in NASA 701, a Lear Jet operated by the NASA Ames Research Center at Moffett Field, California. The telescope views the sky directly through an open port in the side of the aircraft and has a half-peak beamwidth of  $13'$  in elevation and  $10'$  in azimuth and is guided optically

to better than  $6'$ . The signal incident on the detector is chopped by moving the secondary mirror of the telescope at a rate of 80 Hz between two fixed positions, resulting in a center-to-center beam separation of  $14'$  in azimuth. The telescope is thus sensitive to discrete sources of flux or flux gradients but not to constant and uniform instrumental or sky background.

The response of the low-temperature germanium bolometer (Low 1961), operated at  $1.8^\circ\text{K}$ , is essentially flat from  $1.5\ \mu$  to beyond  $300\ \mu$ .

Observations were carried out above the tropopause near an altitude of 50000 feet. Two different filter combinations were used to define the transmission function of the system. The first filter, with transmission cut-on at  $40\ \mu$ , uses 0.46-mm crystalline quartz and a Fabry lens 2 mm thick made of intrinsic silicon, both at  $2^\circ\text{K}$ ; black polyethylene 0.15 mm thick at  $100^\circ\text{K}$ ; and crystalline quartz 0.46 mm thick and high-density polyethylene 3 mm thick at  $300^\circ\text{K}$ . The high-density polyethylene serves as the vacuum window of the Dewar. The half-peak transmission of the system is at  $65\ \mu$ . In the second filter system, high-impact polystyrene 1.5 mm thick was substituted for the polyethylene Dewar window and the warm quartz. This substitution resulted in a transmission cut-on

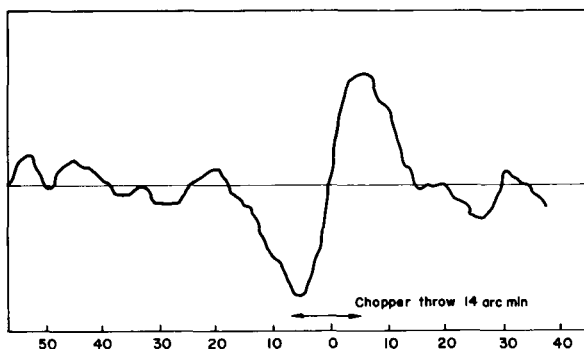


FIG. 1.—A scan through the galactic center perpendicular to the galactic plane

at  $50\ \mu$  and half-peak transmission at  $75\ \mu$ . The passbands of the two systems are essentially determined by warm filters, the transmission characteristics of which were readily measured in the laboratory. Diffraction limits the response of both systems beyond  $350\ \mu$ .

### III. OBSERVATIONS

The galactic center was observed in the far-infrared during flights on 1969 August 21, 22, 25, and 26. The far-infrared position of the galactic center agrees to within our  $6'$  offset-guiding accuracy with the position given by Becklin and Neugebauer (1968) for the  $2.2\text{-}\mu$  source and the radio source Sag A (Downes and Maxwell 1966).

Observations of Mars provided an absolute calibration and a check of the bore sighting. When the polyethylene-quartz filter combination was used, the galactic center produced  $(2.0 \pm 0.1)$  times the deflection observed from Mars; the galactic center/Mars ratio was  $2.1 \pm 0.1$  for the polystyrene filter combination. Both objects were observed on all flights within 30 minutes from each other and were, at that time,  $21^\circ$ – $25^\circ$  above the horizon.

We scanned an area of about 10 square degrees around the galactic center, essentially perpendicular to the galactic plane. A typical scan through the galactic center, using the polystyrene filter, is shown in Figure 1. The separation of the two peaks is equal to the chopper throw of  $14'$ . The scans do not differ significantly from scans through a point

source. The diameter of the galactic nucleus in the far-infrared is less than  $3'$ , which is thus small compared with our  $10'$  beam. Measurements at  $5\text{--}22\ \mu$  (Low *et al.* 1969; Becklin and Neugebauer 1969) have shown that the source consists of a  $15''$  core with wings. Scans approximately  $0^\circ.25$  to the north and south of the galactic center yielded no visible deflections. However, several discrete sources were found along the galactic plane approximately  $0^\circ.5$  south of the galactic center. Specifically, there appears to be a source, which produced about one-fifth the deflection observed from the galactic center, approximately  $40'$  to the southwest at

$$\alpha = 17^{\text{h}}41^{\text{m}} \pm 0^{\text{m}}6, \quad \delta = -29^\circ30' \pm 8'(1950.0).$$

These sources may be satellites of the galactic nucleus, or they may be members of a new class of cool objects distributed throughout the galactic plane. Whatever their nature, it seems that they may contribute significantly to the infrared luminosity of the Galaxy. The extended source reported by Hoffmann and Fredrick (1969) was not detected.

#### IV. DATA REDUCTION

The differential atmospheric-extinction correction for the observed Mars/galactic center ratio was small and could be neglected. The absolute signal measured for Mars, if a far-infrared spectrum corresponding to a blackbody temperature of  $240^\circ\text{K}$  (Aumann, Gillespie, and Low 1969) is assumed, agrees to within a factor of 2 with calculations based on the known characteristics of the telescope, the filters, and the bolometer.

Although our system is primarily designed to measure the total power received over a wide spectral bandwidth, limited information about the flux-density spectrum  $F_*(\nu)$  of the galactic center can be obtained by utilizing the known spectral response of the two different filter systems. In principle, the unknown spectrum could be specified by  $2n$  parameters  $F_*(\nu_1), \nu_1, \dots, F_*(\nu_n), \nu_n$ , if the unknown source and a calibration source with known flux-density spectrum  $F_c(\nu)$  were observed with  $2n$  different wide passband filters. It would require the simultaneous solution of  $2n$  equations

$$\left(\frac{V_*}{V_c}\right)_i \int_0^\infty F_c(\nu) T_i(\nu) d\nu = \int_0^\infty F_*(\nu) T_i(\nu) d\nu, \quad i = 1, \quad 2n, \quad (1)$$

where  $(V_*/V_c)_i$  is the observed signal ratio from the unknown source and the calibration source with flux density spectrum  $F_c(\nu)$  for the  $i$ th filter with system response characteristic  $T_i(\nu)$ . Since our observations of the galactic center were made with only two filter systems, equation (1) reduces to two equations in two unknowns, the location of the peak of the flux-density spectrum,  $\nu_{\text{max}}$ , and its peak value  $F_*(\nu_{\text{max}})$ . For the analytic form of  $F_*(\nu)$  necessary to perform the integrations, we assumed various spikes. This is roughly the behavior expected from extrapolations of previous ground-based observations at  $10$  and  $20\ \mu$  (Low *et al.* 1969; Becklin and Neugebauer 1969) and at  $3.3\text{ mm}$  (Dworetzky *et al.* 1969). At  $1\text{ mm}$  there is an unpublished upper limit of  $5 \times 10^{-25}\text{ W m}^{-2}\text{ Hz}^{-1}$  obtained recently with a  $1'$  beam by one of us (F. J. L.).

Calculations were made for three spectra:

a) Power-law spectrum:

$$F_*(\nu) = \begin{cases} F_{\text{max}} \left(\frac{\nu}{\nu_{\text{max}}}\right)^{-\alpha}, & \nu \geq \nu_{\text{max}} \\ F_{\text{max}} \left(\frac{\nu}{\nu_{\text{max}}}\right)^{\beta}, & \nu < \nu_{\text{max}}. \end{cases} \quad (2)$$

The spectrum  $F_*(\nu)$  was forced through the  $10\text{-}\mu$  observations and the  $1\text{-mm}$  upper limit.

b) The same power-law spectrum as above, but with  $F_*(\nu)$  forced through the  $22\text{-}\mu$

observation and the 1-mm upper limit. A steep and narrow power-law spectrum may be produced by coherent synchrotron radiation (Zheleznyakov 1967).

c) A spectrum resembling that produced by a monoenergetic electron synchrotron source with a synchrotron self-absorption cutoff,

$$F_*(\nu) = \begin{cases} F_{\max} \left( \frac{\nu}{\nu_{\max}} \right)^{1/2} \exp \left( 1 - \frac{\nu}{\nu_{\max}} \right), & \nu \geq \nu_{\max} \\ F_{\max} \left( \frac{\nu}{\nu_{\max}} \right)^{2.5}, & \nu < \nu_{\max} \end{cases} \quad (3)$$

The results are listed in Table 1. The location and the peak value of the flux,  $(8 \pm 3) \times 10^{-21} \text{ W m}^{-2} \text{ Hz}^{-1}$  at  $(4.2 \pm .2) \times 10^{12} \text{ Hz}$ , do not depend strongly on the assumed shape of the spectrum.

TABLE 1  
CALCULATED FLUX FROM THREE SPECTRA

PARAMETER	OBSERVED FLUX	CALCULATED FLUX		
		Power-Law Spectrum		Synchrotron Spectrum
		(a)	(b)	(c)
$F(10 \mu)^*$ .....	$1 \times 10^3$	$10^3$	40	$2.5 \times 10^3$
$F(22 \mu)^*$ .....	$2 \times 10^3$	$1 \times 10^4$	$2 \times 10^3$	$8 \times 10^4$
$F(1 \text{ mm})^*$ .....	$< 50$	50	50	$1.1 \times 10^3$
$\nu_{\max}$ .....	...	$4.1 \times 10^{12}$	$4.2 \times 10^{12}$	$4.2 \times 10^5$
$F_*(\nu_{\max})^*$ .....	...	$9.5 \times 10^5$	$1.1 \times 10^6$	$6.5 \times 10^5$
$\alpha$ .....	...	3.5	5.05	expon.
$\beta$ .....	...	3.8	3.8	2.5
$L_{\text{tot}} (L_{\odot})$ .....	...	$6 \times 10^7$	$5.2 \times 10^7$	$1.1 \times 10^8$
$L_{50-350 \mu} (L_{\odot})$ ..	...	$2.8 \times 10^7$	$3 \times 10^7$	$5 \times 10^7$

\* In flux units (1 f.u. =  $10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$ ).

If a distance of  $10^4 \text{ pc}$  is assumed, then the total integrated infrared flux from the galactic center,  $(2.8 \pm 1.0) \times 10^{-5} \text{ erg sec}^{-1} \text{ cm}^{-2}$ , corresponds to a total power output  $L_{\text{tot}} = (8 \pm 3) \times 10^7 L_{\odot}$ , approximately 50 percent of which contributes to the observed signal  $L_{50-350 \mu}$ . The present results, along with previously published data, are plotted in Figure 2.

The indicated error bars reflect the uncertainties in the assumed spectra; they do not include the uncertainty in the absolute calibration which is probably accurate to better than 50 percent.

#### V. DISCUSSION

The spectral power distribution shown in Figure 2 may not represent the intrinsic radiative properties of the source but may be affected by effects of beam size and by absorption in the intervening medium. The ground-based observations between 5 and  $25 \mu$  were made with a  $25''$  beam, the new upper limit of  $50 \times 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$  at 1 mm was established with a  $60''$  beam, while the 3-mm point is based on a  $180''$  beam (Dworetzky *et al.* 1969). The beam used in our observations with the airborne infrared telescope had an effective diameter of  $720''$ . The importance of effects of beam size thus needs to be investigated. The apparent structure in the spectrum may be produced by solid-state absorption in the particulate matter which produces the  $\sim 25 \text{ mag}$  of visual extinction

(Becklin and Neugebauer 1968). Again, this needs to be investigated by further observations.

A clear distinction should be made between the thermal reradiation dust models and nonthermal models. Unfortunately, this issue is difficult to settle by observations of the galactic center alone, since various methods of heating the dust can be devised along with complicated geometrics.

In the simplest case of an optically thick dust cloud heated by internal sources to a temperature of  $43^\circ\text{K}$ , so that the peak would be at  $70\ \mu$ , the diameter must be larger than  $1.3 \times 10^{19}\text{ cm}$  to produce the total observed flux. Since the observed size of the source lies between  $1.4 \times 10^{18}$  and  $1.4 \times 10^{19}\text{ cm}$ , models of this kind are ruled out. Clearly the spectrum is much steeper than a Planck distribution. However, it is possible to postulate a model containing dust which has a broad resonant absorption near  $70\ \mu$ ,

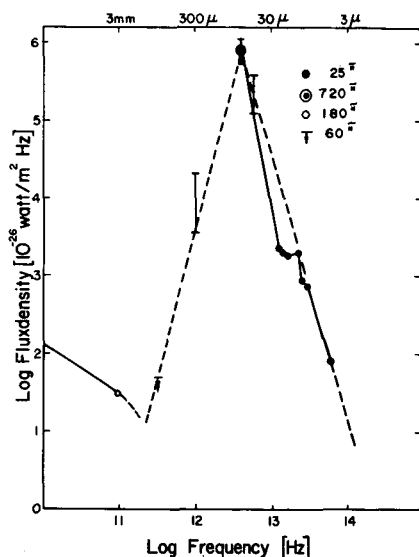


FIG. 2.—Spectral flux distribution of the galactic nucleus. Data on  $5\text{--}20\ \mu$  taken with  $25''$  beam (Low *et al.* 1969); present data taken with  $720''$  and  $60''$  beams;  $3.3\text{-mm}$  data taken with  $180''$  beam (Dworetzky *et al.* 1969).

so that the dust temperature would be high enough to produce the required flux from a small volume. Therefore, dust may play a role in the galactic nucleus, but its contribution to the infrared luminosity is probably small.

In discussing nonthermal models of this source we have already reached the conclusion that, in the case of an electron-synchrotron model, a single magnetic field and distribution of particles cannot occupy the observed volume (Low *et al.* 1969); instead, the source must be made up of many smaller components. This point is carried further in an accompanying paper (Low 1970).

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